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Report Title

Quantum logic with cold neutral atoms

ABSTRACT

An experimental and theoretical study of neutral atom qubits for use in a quantum computing device was performed. Experimental achievements include loading and detection of single Rb87 atoms in optical traps, demonstration of fast (1.4 MHz) Rabi rotations between ground hyoperfine states, measurement of 1 ms T2 time using Ramsey inetrferometry, and observation of partial Rydberg blockade by two-photon excitation to levels with n=47.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. M. Saffman and T. G. Walker, "Creating single atom and single photon sources from entangled atomic ensembles", Phys. Rev. A 66, 065403-1--4 (2002).

2. M. Saffman, "Addressing atoms in optical lattices with Bessel beams", Opt. Lett. 29, 1016-1018 (2004).

3. T. G. Walker and M. Saffman, "Zeros of Rydberg-Rydberg Föster interactions", J. Phys. B: At. Mol. Opt. Phys. 38, S309-S319 (2005).

4. M. Saffman and T. G. Walker, "Analysis of a quantum logic device based on dipole-dipole interactions of optically trapped Rydberg atoms", Phys. Rev. A 72, 022347 (2005).

5. M. Saffman and T. G. Walker, "Entangling single and N atom qubits for fast quantum state detection and transmission", Phys. Rev. A 72, 042302 (2005).

6. D. D. Yavuz, "Single photon SWAP gate using electromagnetically induced transparency", Phys. Rev. A 71, 053816 (2005).

7. D. D. Yavuz, "Refractive Index Enhancement in a Far-Off Resonant Atomic System", Phys. Rev. Lett. 95, 223601 (2005).

8. D. D. Yavuz, P. B. Kulatunga, E. Urban, T. A. Johnson, N. Proite, T. Henage, T. G. Walker, and M. Saffman, "Fast Ground State Manipulation of Neutral Atoms in Microscopic Optical Traps", Phys. Rev. Lett. 96, 063001 (2006).

Number of Papers published in peer-reviewed journals: 8.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

1. S. Chutia, J. O. Day, E. Urban, T. A. Johnson, P. B. Kulatunga, T. G. Walker, M. Saffman, "Design of a Rydberg gate quantum logic experiment", (2003). Proceedings, Published in Bulletin of the American Physical Society, vol. 48, page J1 35 DAMOP meeting (Boulder, May, 2003).

2. P. B. Kulatunga, D. D. Yavuz, T. A. Johnson, N. Proite, E. Urban, T. G. Walker, and M. Saffman, "Loading and quantum state control of atoms in microscopic optical traps", (2005). Proceedings, Published
in Bulletin of the American Physical Society - proceedings of DAMOP 2005 meeting (Lincoln, May 2005).

3. M. Saffman, D. Yavuz, M. Delaney, P. Kulatunga, T. Johnson, E. Urban, T. Henage, N. Proite, T. Walker, "Quantum state control of atoms in microscopic optical traps", (2006). Proceedings, Published
in Bulletin of the American Physical Society Abstract U40.00006, March meeting, (Baltimore, March 2006).

4. D. Yavuz, E. Urban, T. Johnson, P. Kulatunga, M. Delaney, T. Henage, N. Proite, T. Walker, M. Saffman, "Fast Ground State Manipulation of Neutral Atoms in Microscopic Dipole Traps", (2006). Proceedings, Published in Bulletin of the American Physical Society, DAMOP meeting, (Knoxville, May 2006).

Number of Papers published in non peer-reviewed journals: 4.00

(c) Papers presented at meetings, but not published in conference proceedings (N/A for none)

1. M. Saffman, "Quantum computing using Rydberg atom
dipole-dipole interactions", presented at Neutral Atom Quantum Computing Workshop, (NIST, Gaithersburg, June, 2002).

2. M. Saffman, "Quantum information processing with
two-dimensional atomic arrays", presented at NSF Qubic program review, (Ft. Lauderdale, May 14, 2003).

3. M. Saffman, "Photons on demand with controlled spatial modes from a phased array of excited atoms", presented at Workshop on Quantum Information and Ordered Systems, NORDITA, (Copenhagen, Sep. 13, 2003).

4. M. Saffman, "Neutral atom quantum computing: the experimental status", presented at Workshop on Neutral Atom Quantum Computing, Research Laboratory for Electronics, MIT, (Cambridge, Dec. 13, 2003).

5. M. Saffman, "Fast Rydberg gate quantum logic and state detection with single and collective atomic qubits", presented at Workshop of the European QUEST program, (La Thuile, Italy, March 12, 2004).

6. M. Saffman, "Cross entanglement of single and N atom qubits
for Quantum state transmission", presented at Quantum Optics Summer School, Niels Bohr Institute, (Copenhagen, Aug. 21, 2004).

Number of Papers not Published: 6.00

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED	
Erich Urban	0.50	No
Todd Johnson	0.50	No
Thomas Henage	0.50	No
Sucismita Chutia	0.50	No
Larry Isenhower	0.50	No
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Deniz Yavuz	0.90	No
Marie Delaney	0.10	No
FTE Equivalent:	**1.50**	
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Mark Saffman	0.10	No
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Total Number:	**2**	

Names of Under Graduate students supported

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Stephen Neal	0.50	No
Nicholas Proite	1.00	No
John Rohde	1.00	No
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Total Number:	**4**	

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NAME

Total Number:

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

August 15, 2006

Quantum logic with cold neutral atoms

This project started in 2002 with the goal of experimentally demonstrating quantum logic gates with trapped neutral atoms, as well as theoretical studies of the feasibility of two-dimensional arrays of quantum gates. We have made significant experimental and theoretical progress towards demonstrating neutral atom quantum gates. Details of the scientific progress are given in the following sections.

Experimental results:

- loading of single Rb87 atoms into a microscopic optical trap
- demonstration of site specific, fast (1.4 MHz) rotations between the qubit basis states using stimulated Raman transitions
- demonstration of site specific rotations with crosstalk at the level of 0.001 for sites separated by 8 μm.
- measurement of T2=0.9 msec using Ramsey interferometry
- demonstration of fast two-photon excitation of n=28 Rydberg states
- spectroscopic observation of Rydberg levels ranging up to n=55
- observation of dipole-blockade suppression of multiple excitation of atoms in a microscopic optical trap.
- demonstration of loading of atoms in a 2x3 mini-lattice of optical sites.

The results related to loading and control of ground state atoms were published in Physical Review Letters in spring 2006 (Yavuz, et al. Phys. Rev. Lett. **96**, 063001 (2006)). That work demonstrated the ability to load and detect single atoms and coherently control the qubit state at a rate of Omega=1.4 MHz. The qubit coherence time was measured by Ramsey interferometry to be about T2= 900 microsec. The corresponding figure of merit Omega*T2 ~1300 is, to our knowledge, the best ever reported for manipulation of neutral atom qubits.

In order to demonstrate a neutral atom two-qubit gate we need to have controllable two-atom interactions. The work during the last 9 months has therefore focused on coherent excitation of Rydberg states, and studies of dipole-dipole interactions of Rydberg atoms.

Work was completed on a two-color stabilized laser system with each laser stabilized at the 100 Hz level by locking to a very high finesse cavity. The lasers were used for Rydberg excitation. An example showing the spectrum of the 55s state is shown in Fig. 1. The lineshape is derived from measurements of the trap loss. Accounting for power broadening and Doppler broadening the theoretical FWHM of the line is about 1.9 MHz which agrees reasonably well with the observed 2.2 MHz.

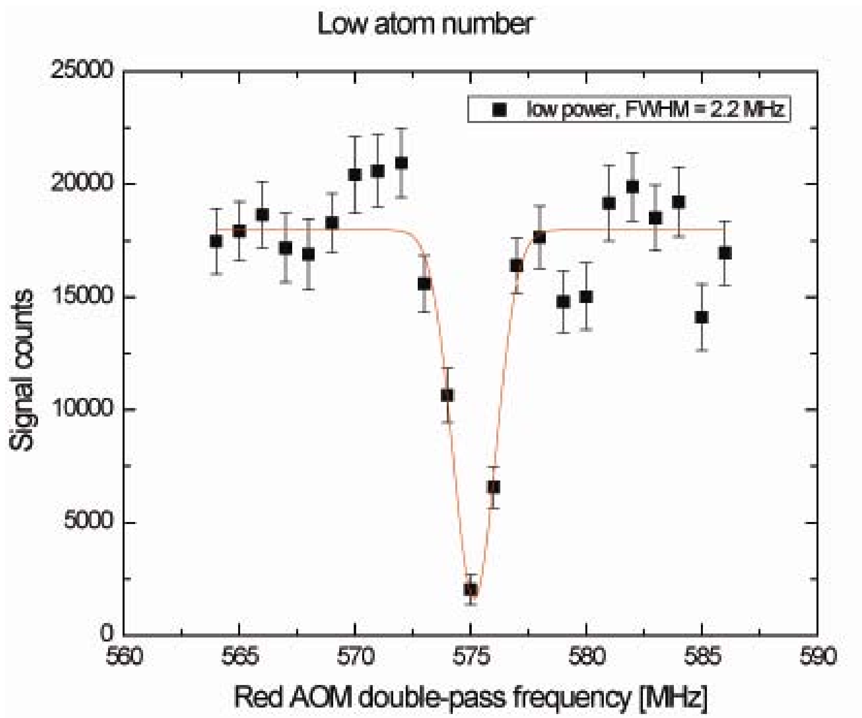

Figure 1. Spectroscopy of the 55s Rydberg level.

We have also investigated Rydberg excitation in the time domain using the 28d level. Figure 2 show the ability to put significant population in the Rydberg state at time scales as short as a few hundred nsec. About 50% population transfer is observed, and only about half of a full Rabi period. The green curve is the result of numerically solving the optical Bloch equations, including excited state decay out of the system and an intrinsic dephasing mechanism. The source of the dephasing is currently under study. It may be due to two-body interactions of Rydberg atoms. While this is not fully expected at n=28, the data for 10 atoms in the trap show significantly smaller population transfer, possibly due to blockade effects.

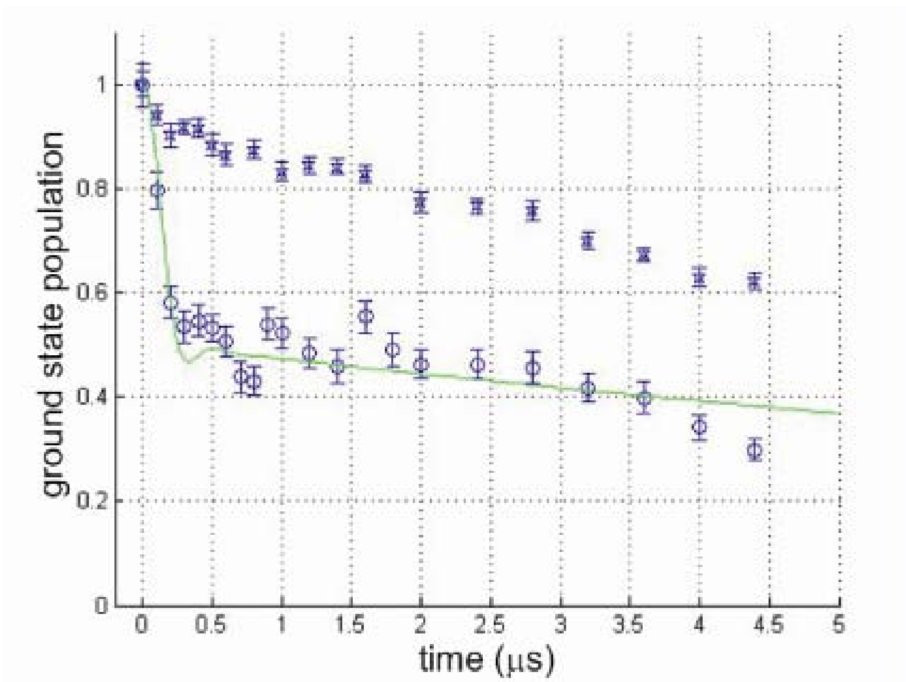

Figure 2. Time evolution of the ground state population during coherent excitation of the 28d5/2 level. The lower curve is for an average of 2 atoms in the optical trap and the upper curve is for an average of 10 atoms. The green line is a simulation result.

We have therefore studied the blockade physics in more detail by varying the number of atoms loaded. Figure 3. shows the fractional trap loss as a function of the number of atoms in the optical trap. For excitation to 55s the atoms are only weakly interacting (due to the large energy defect of the 55s Forster interaction) and we see a fractional loss that is almost independent of the number of atoms. However, for excitation to 47d5/2 (small energy defect and strong Forster interaction) we see a fractional loss very close to the 1/n curve that applies for perfect dipole blockade. A publication describing these results is in preparation.

This data is the first time that the dipole blockade mechanism has been seen in a controlled experiment with a small number of atoms in an optical trap. As such it represents a significant step towards implementing a two-qubit gate using dipole-dipole interactions. Work in progress is studying the sources of dephasing seen in Fig. 2, and investigating choices of parameters in order to obtain higher fidelity blockade. We plan, in the near future, to study the use of atoms in one trap to block the excitation of atoms in a neighboring trap located 8 microns apart. We demonstrated last year that we can coherently control one trap without disturbing the neighboring trap using stimulated Raman beams. By combining those capabilities with Rydberg excitation we will be within sight of a full 2-qubit gate.

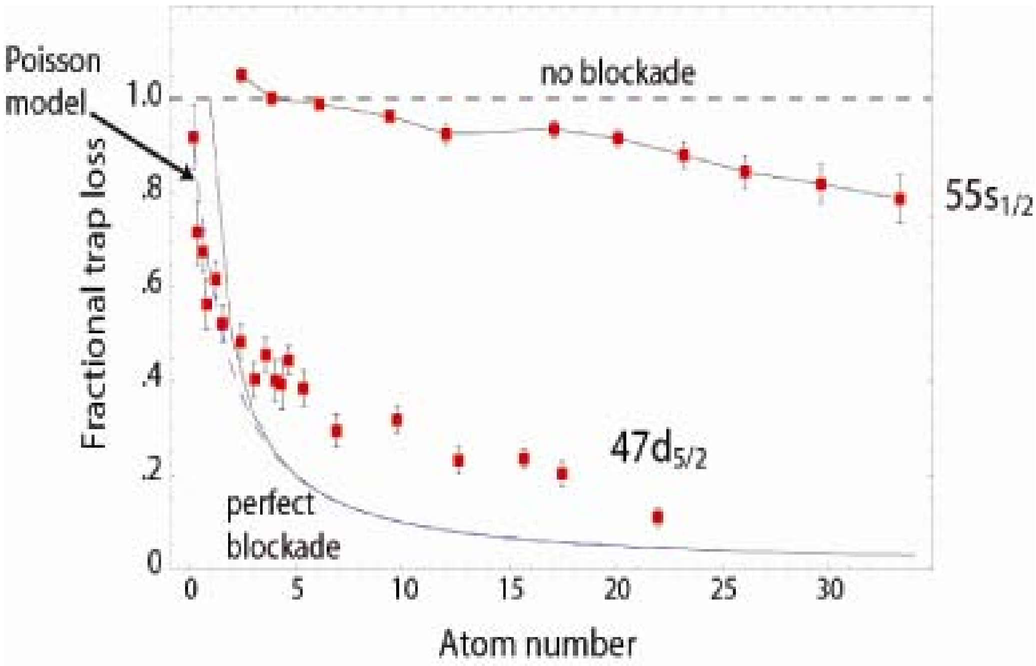

Figure 3. Observation of dipole blockade in a microscopic trap. The 1/n theory curve is corrected at small n for the Poissonian loading statistics.

Finally as a first step towards scalability we have demonstrated loading of a 2x3 array of optical traps, as shown in Fig. 4. The spots were created by combining a custom fabricated diffraction grating with a calcite beamsplitter to obtain a two-dimensional array.

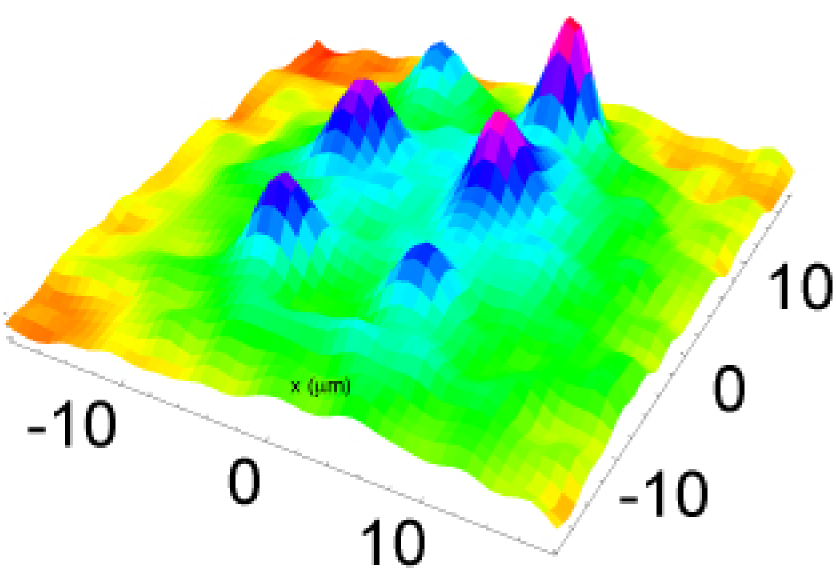

Figure 4. Picture of atoms loaded into a 2x3 array. Trapping power of 100 mW at 1030 nm per spot.

The traps were viewed in backscatter using a dichroic mirror inserted in the optical train that creates the spot array. Trapping was achieved using about 100 mW per spot. A 30 W infrared laser which is readily available commercially would thus provide adequate power for a 100 site or more array.

Theoretical results

We have studied how Rydberg blockade can be used for single atom deterministic loading and deterministic generation of single photons (M. Saffman and T. G. Walker, Creating single atom and single photon sources from entangled atomic ensembles", Phys. Rev. A 66, 065403-1--4 (2002)).

In the last 12 months we have published two theoretical papers related to the Rydberg gate approach.

1) A detailed theoretical analysis of the operation of a neutral atom Rydberg gate (M. Saffman and T. G. Walker, “Analysis of a quantum logic device based on dipole-dipole interactions of optically trapped Rydberg atoms”, Phys. Rev. A (2005)). The analysis confirms the potential for high fidelity gates operating at MHz rates, and provides a theoretical basis for evaluating our ongoing experimental progress.

2) A proposal for using single atom qubits coupled to small mesoscopic ensembles for fast state readout and quantum networking (M. Saffman and T. G. Walker “Entangling single and N atom qubits for fast quantum state detection and transmission”, Phys. Rev. A (2005)). This paper shows a pathway to scalable quantum networking without the need for the challenging task of strong coupling between atoms and photons in ultra high finesse optical resonators.

We are currently working on several theoretical topics related to our current Rydberg experiments. This includes studies of dipole blockade using microwave dressing of Rydberg states, and approaches to efficient generation of GHZ, multipartite entanglement, by coupling of multiple Rydberg levels. In collaboration with Klaus Moelmer (University of Aarhus, Denmark) we are preparing a manuscript which shows how the Rydberg gate can be used for efficient encoding into decoherence free subspaces. In this encoding each logical qubit is represented by two physical qubits such that the qubit basis states are immune to common perturbations.